Merger-Driven Transients: NS-NS, NS-BH, BH-BH

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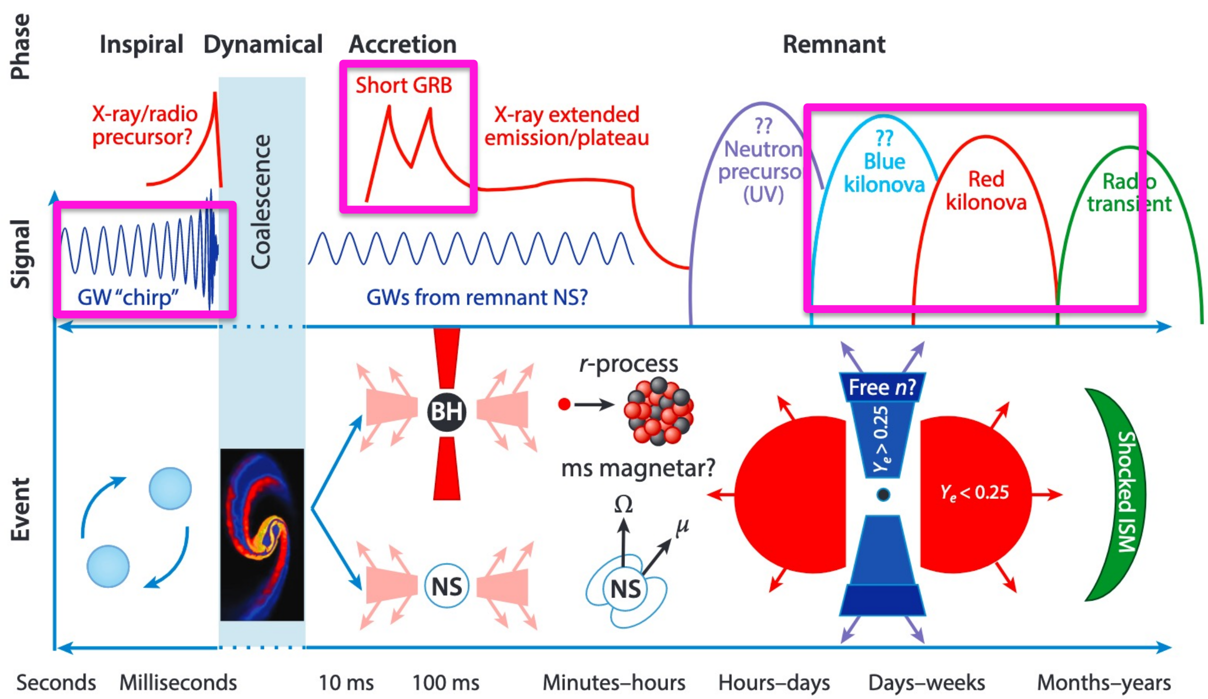
GW170817 and the start of multi-messenger astronomy

Fernandez & Metzger, ARNPS, 2016, 66, 23



- ✓ 1st **BNS** detected in **GWs**
- ✓ 1st **EM counterpart** of a GW merger
- ✓ 1st direct short **GRB-BNS** merger association
- ✓ 1st clear discovery of a **kilonova** as site of **r-process**
- ✓ 1st clear detection of an **off-axis GRB**
- ✓ 1st clear observation of a **structured GRB jet**
- ✓ 1st GW **standard siren** Hubble constant constraint
- ✓ 1st test of the **speed of light vs gravity** with GW+EM

Fundamental science questions needing answers

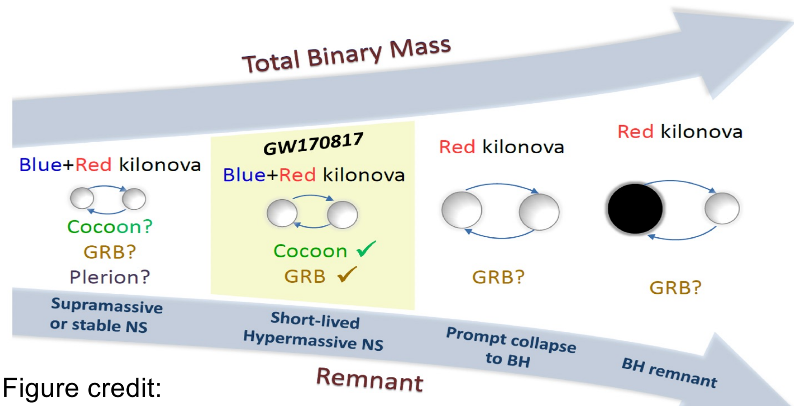
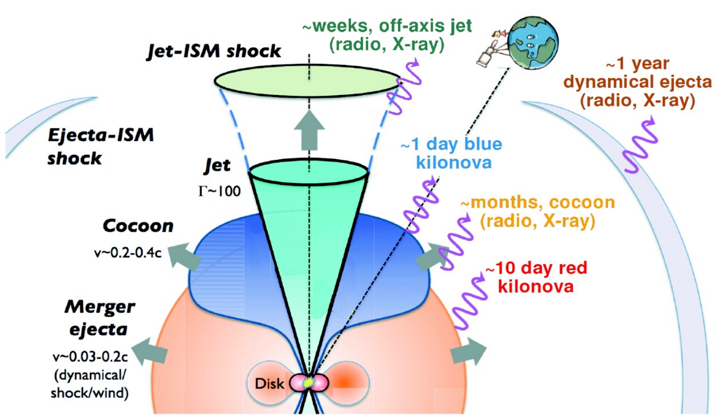


Figure credit: JAGWAR



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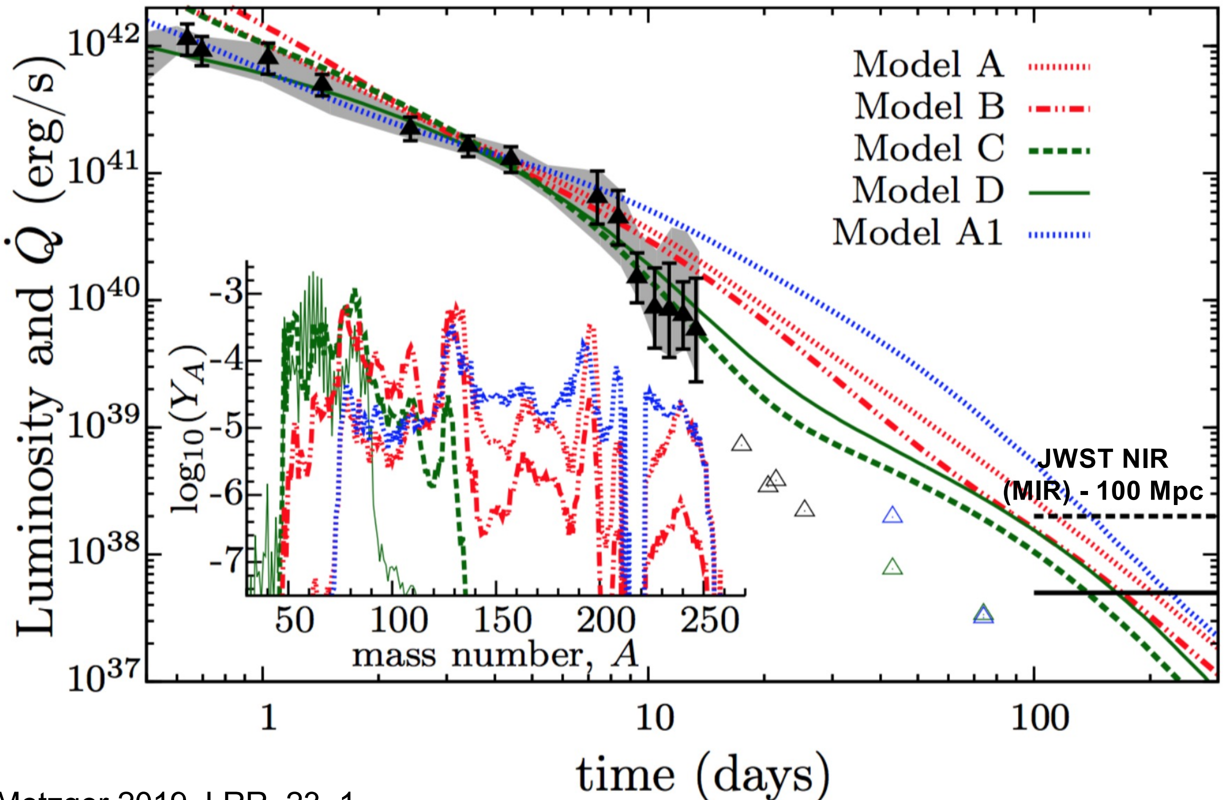
4. Physics of the progenitors via **EM precursors** and relation to the progenitors.

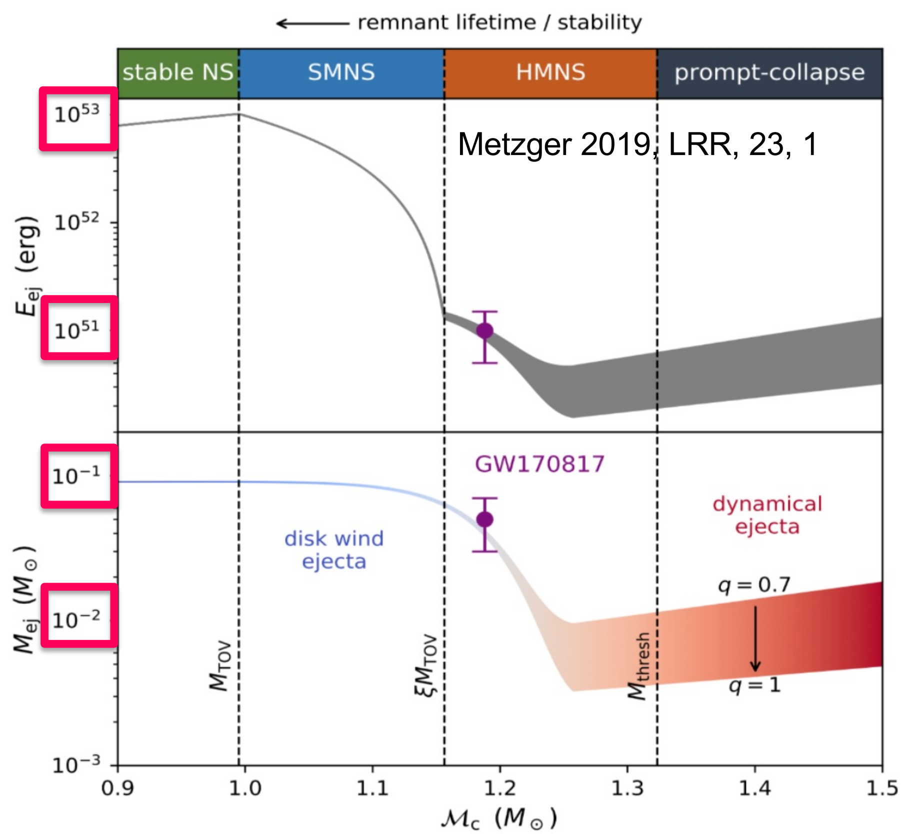
R-process and kilonova ejecta

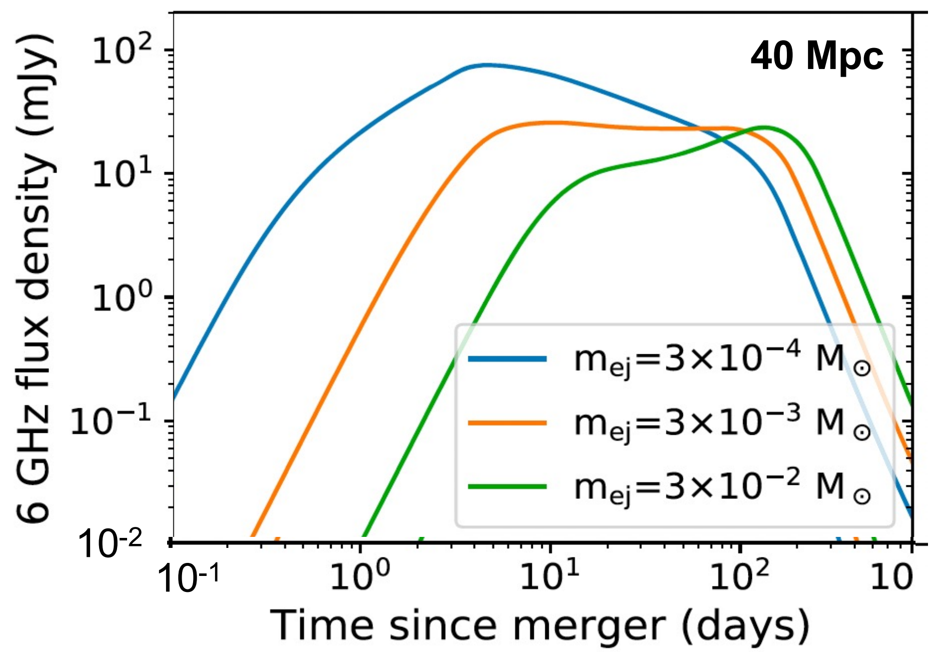


Metzger 2019, LRR, 23, 1

- Bolometric luminosity of the GW170817 kilonova. Colored lines are ejecta heating rate for models with different values for the ejecta mass and average electron fraction.
- Corresponding r-process abundance distributions at t = 1 d shown in the inset.
- Are BNS mergers the only site or one of many sites? Are the heaviest of the heavy elements synthesized? Does the yield of various heavy elements match the solar one?

Kilonova → Ejecta → Progenitors / remnants

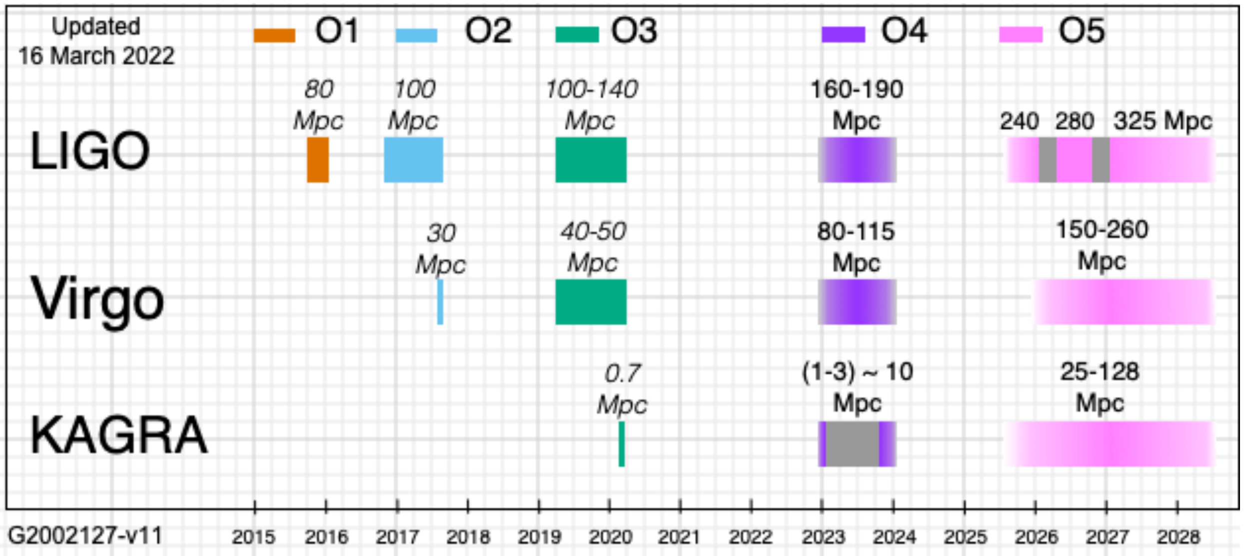




Lazzati & Perna 2019, ApJ, 881, 89

LIGO-Virgo network over the next few yrs

O4 should see more 3 detector events, and those will have better localization.



Note: GW distance horizons are 2.26x farther.

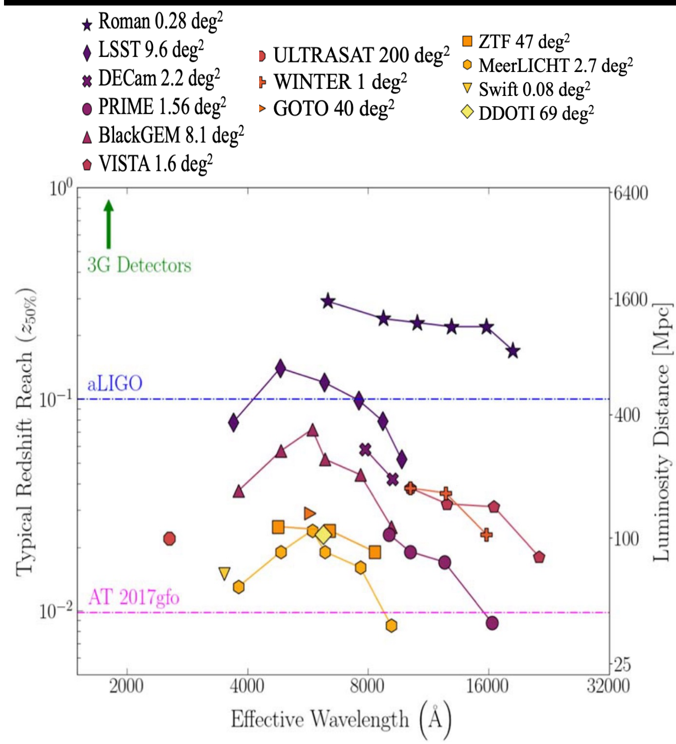
https://www.ligo.org/scientists/GWEMalerts.php

Rate of NS-NS detections with 90% credible areas ≤100 deg^2 (Petrov et al. 2022):

0-1 yr^{-1} in O3 (consistent with true outcome of zero) / 1-13 yr^{-1} in O4 / 9-90 yr^{-1} in O5

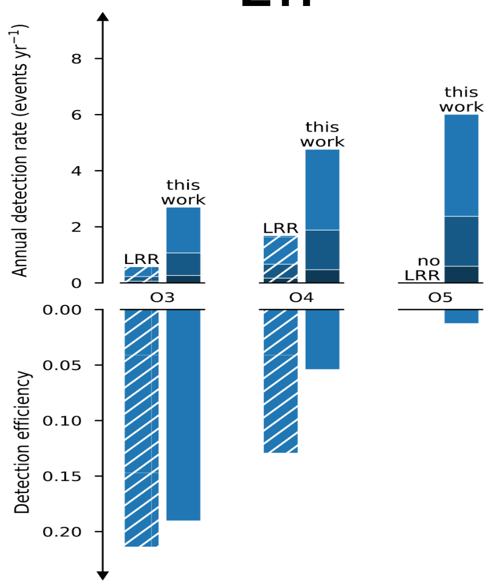
Rate of BH-NS with 90% credible areas ≤100 deg^2: ~10 yr^{-1} in O4 / ~90 yr^{-1} in O5 (Petrov et al. 2022 – Fig.2)

Optimized kilonova searches in O5 (NS-NS)



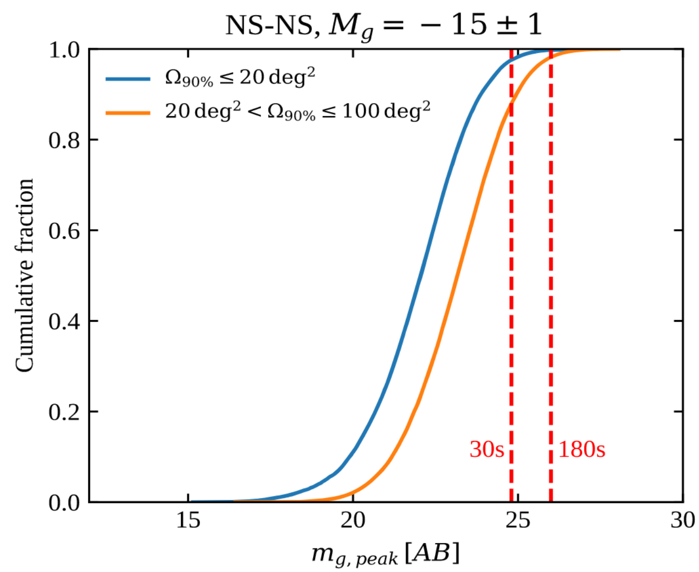
Chase et al. 2022, ApJ, 927, 163

ZTF



Petrov et al. 2022, ApJ, 924, 54

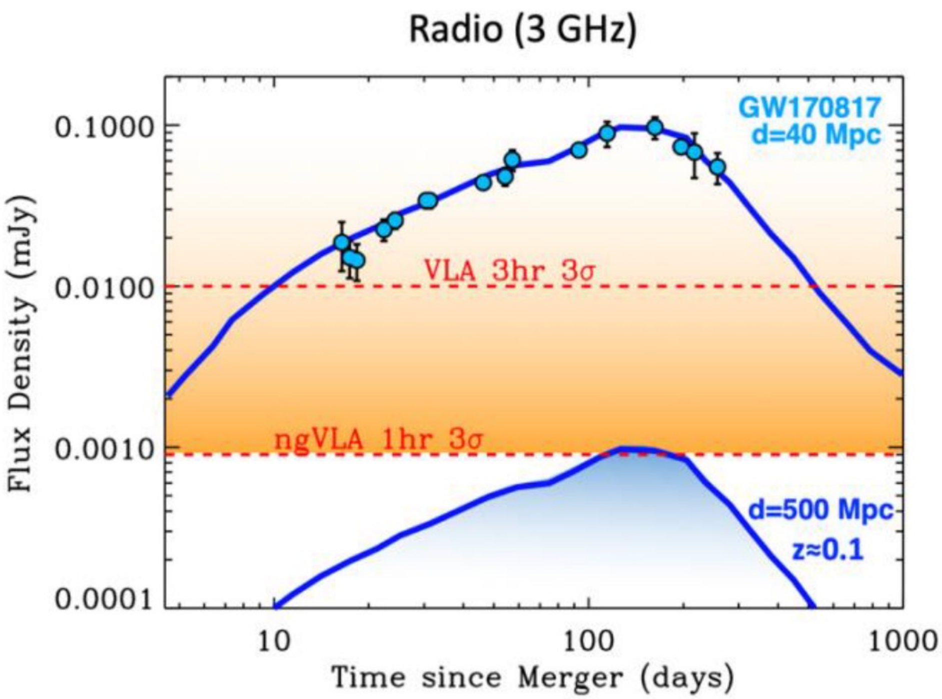
Rubin (ToO)



Andreoni et al. 2022, ApJ, 260, 18

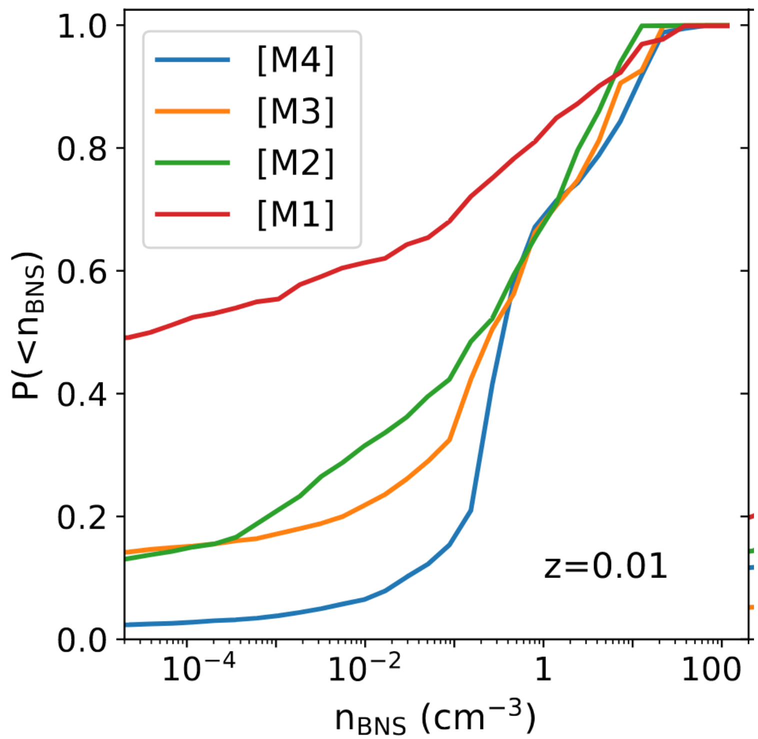
Radio afterglows of NS-NS mergers

Beasley et al. ASTRO-2020 White Paper

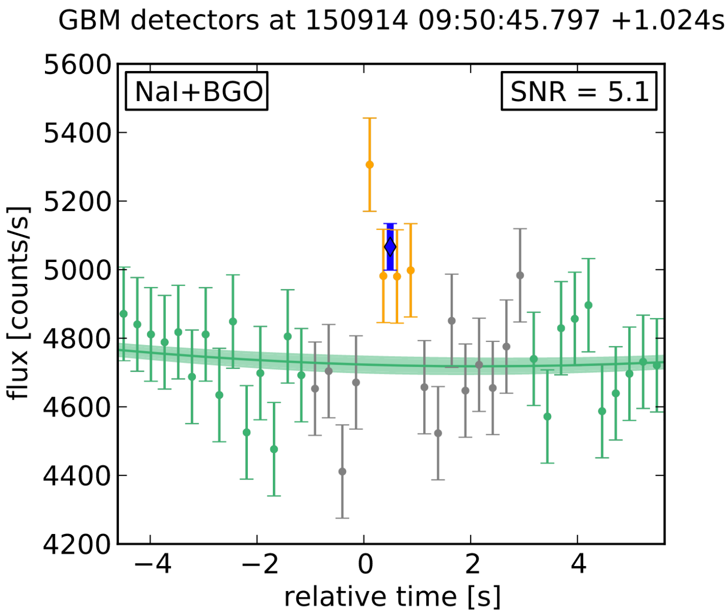


https://ngvla.nrao.edu/

Perna et al. 2022, MNRAS, 512, 2654

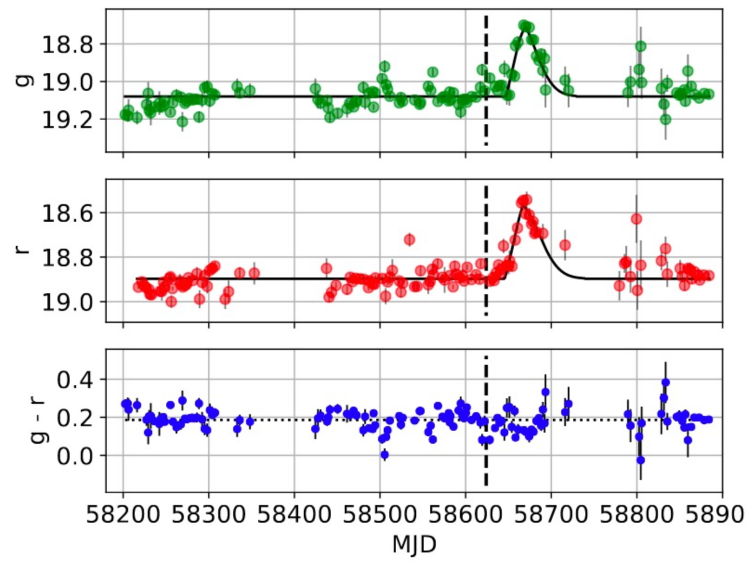


Do BH-BH mergers have EM counterparts?



Connaughton et al. 2016, ApJL, 826, L6

Fermi/GBM tentative γ-ray counterpart, within 1s of GW150914 (Connaughton et al. 2016). Low-statistics event, but enough interest to spur ideas that could explain such emission.



Optical counterpart to GW190521 consistent with expectations for a BH-BH merger in the accretion disk of an active galactic nucleus (AGN).

Graham et al. 2020, Phys. Rev. Lett. 124, 251102

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- Time-domain/multi-wavelength observations critical for answering these questions?
  - ***GW observations of well-localized (<= 100 deg^2) BNS, BH-NS, BH-BH.***
  - ***Mapping jet/kilonova outputs/structures (panchromatic EM observations) to progenitors (GWs).***

- Prospects for detection in the next 10 years?
  - ***Within ~5 yrs: ~10 BNS with GW localizations < 100 deg^2 and with d_L<~ 450 Mpc (enabling kilonova detections).***
  - ***Prospects for detecting BH-NS have larger uncertainties.***

- What is needed?
  - ***> 1 EM+GW detections is top priority!***
  - ***LIGO-Virgo-KAGRA;***
  - ***Large FOV optical/IR facilities, ground-based wide-field IR surveyors, space-based Roman, JWST spectroscopy;***
  - ***Sensitive radio (VLA/ngVLA) and X-ray (Chandra-like) telescopes for follow-up;***
  - ***Time-allocation committees willing to enable follow up of well-localized BH-BH…***

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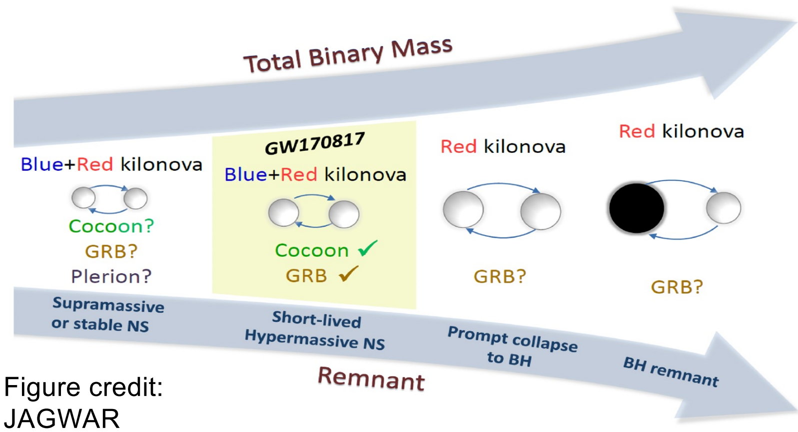
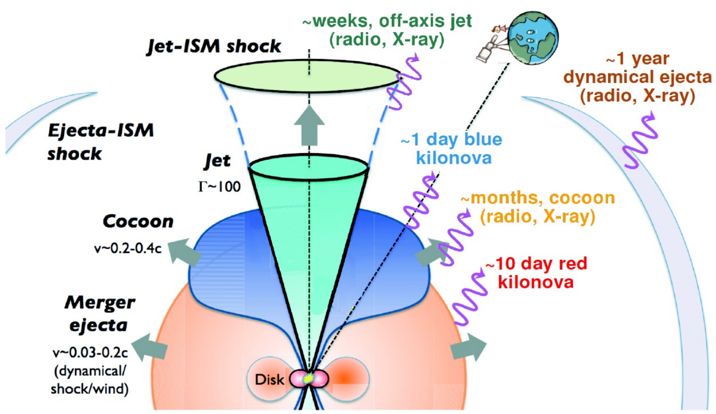


Figure credit: JAGWAR



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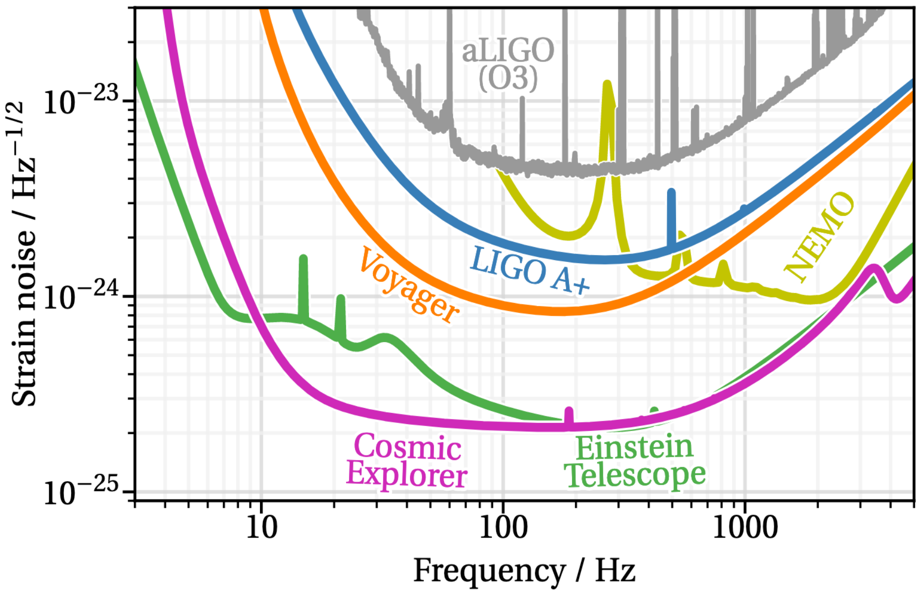
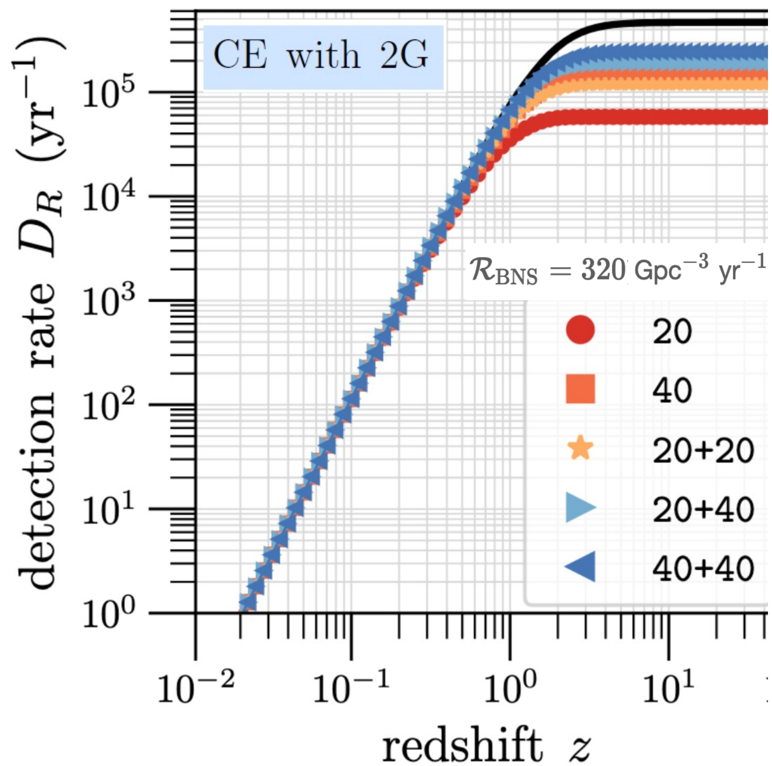
Ground-based XG GW detectors - cosmicexplorer.org



Evans et al., Cosmic Explorer Horizon Study (arXiv:2109.09882)

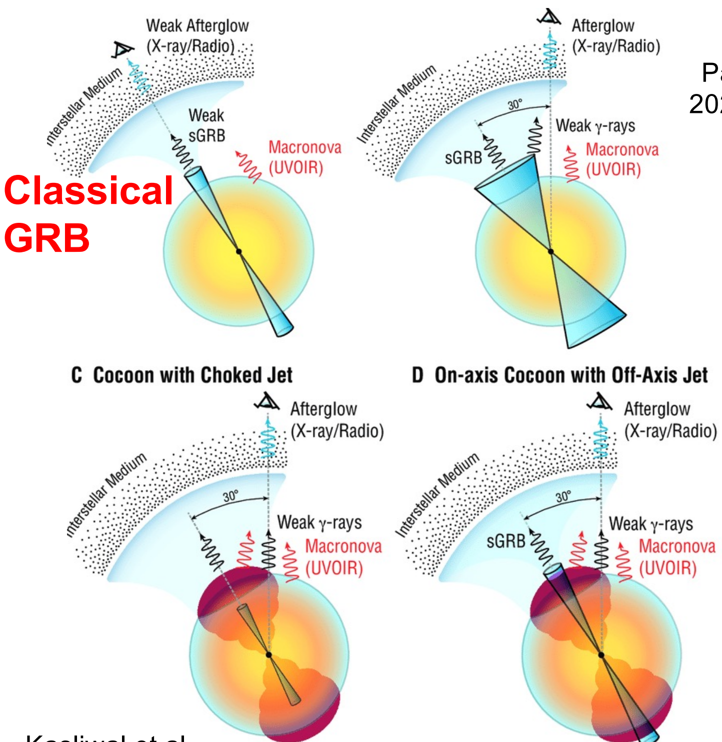


Metric	Ω_{90} (deg^2)		
Quality	≤ 1	≤ 0.1	≤ 0.01
HLVKI+	6	1	0
ECS	2,200	77	2

NS-NS/yr SNR >=10

Ssohrab & Sathyaprakash arXiv:2202.11048

Short GRBs and NS-NS/BH-NS: mapping progenitor properties to jets' existence and properties



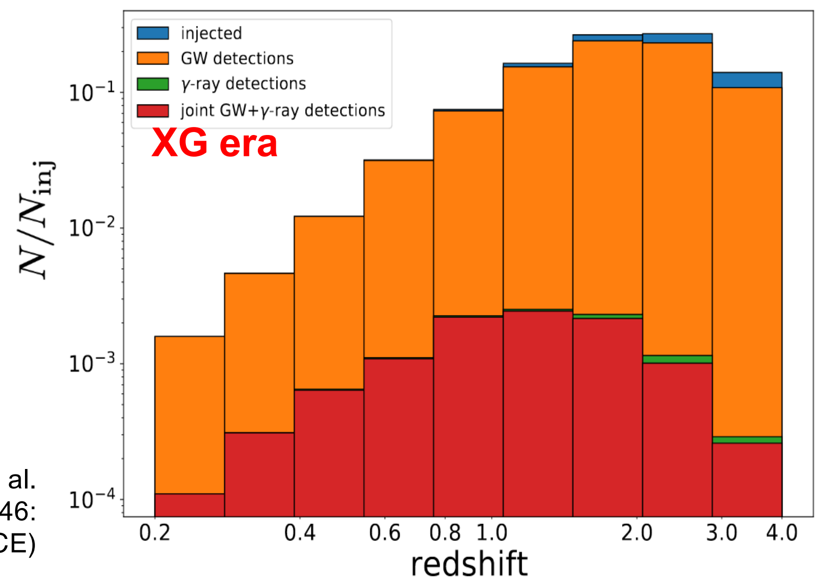
Kasliwal et al., Science, 358, 1559

GW170817

Patricelli et al. 2022, MNRAS, 513, 4159

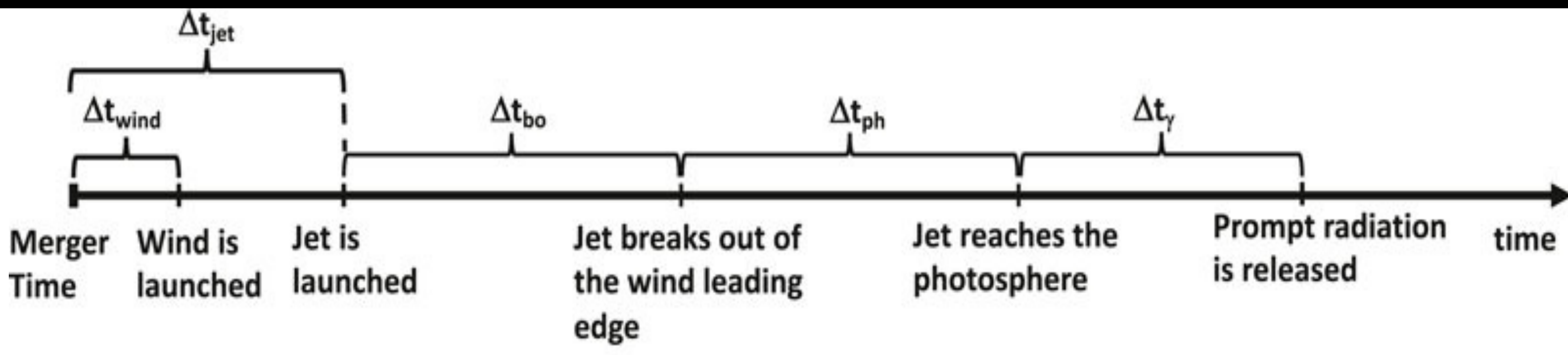
O4 LVK

$\mathcal{R}(0)$	GW	Swift/BAT		Fermi/GBM	
		uniform	structured	uniform	structured
$\mathrm{Gpc^{-3}yr^{-1}}$	$\mathrm{yr^{-1}}$	$\mathrm{yr^{-1}}$	$\mathrm{yr^{-1}}$	$\mathrm{yr^{-1}}$	$\mathrm{yr^{-1}}$
31	5	0.002 (0.01)	0.05-0.08	0.014 (0.06)	0.27-0.46
258	22	0.01 (0.04)	0.24-0.37	0.06 (0.26)	1.17-2.00
765	61	0.03 (0.12)	0.67-1.05	0.18 (0.74)	3.28-5.65



Ronchini et al. arXiv:2204.01746: Fermi-GBM+(ET+CE)

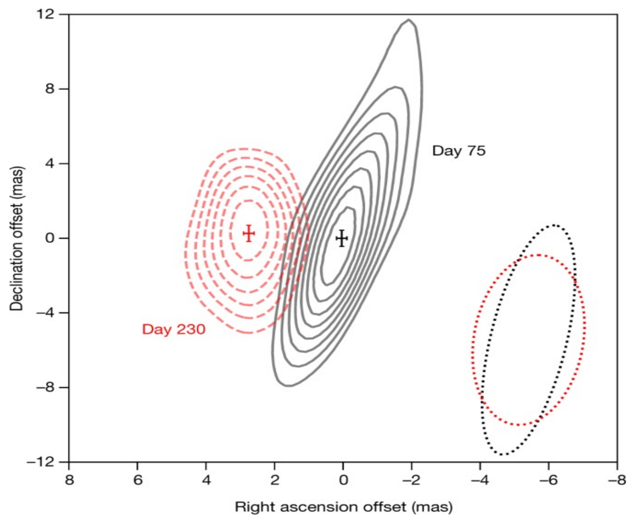
Origin of the GW-EM delay



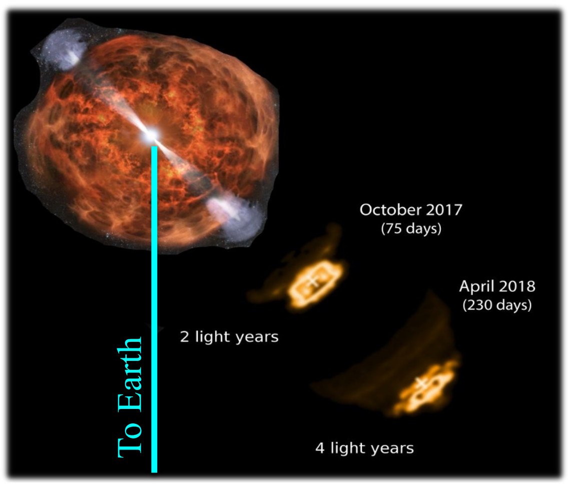
Lazzati 2020, FrASS, 7, 78

Well-localized nearby events: Late-time VLBI observations

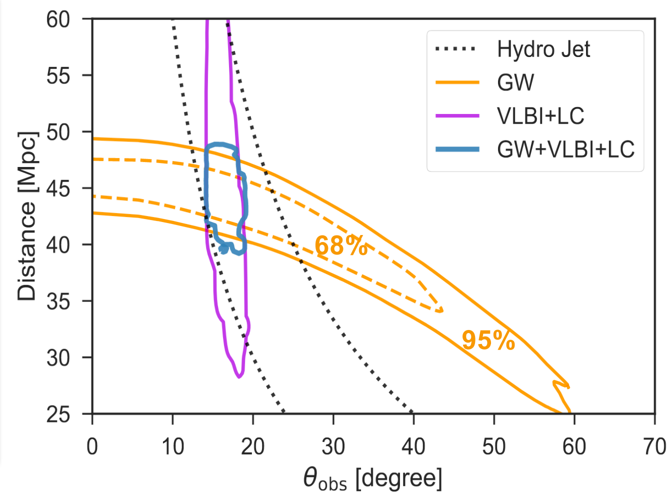
- GW170817 VLBI constraints: ~5 deg jet core pointed ~20 deg away from Earth blasting outwards at over 0.97c.
- ~15 more localized GW170817-like events could bring resolution to the tension in H_0 measurement between Planck CMB and Cepheid-supernova measurements (as compared to 50–100 GW events alone).



Mooley et al. 2018, Nature, 561, 355
Also Ghirlanda et al. 2019, Science, 363, 968



Credit: Berry, Gottlieb, Mooley, Hallinan, NRAO/AUI/NSF



Hotokezaka et al. 2019, Nature Astron., 3, 940

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- Time-domain/multi-wavelength observations critical for answering these questions?
  - ***Mapping progenitors (GWs) to GRBs in a systematic fashion;***
  - ***Systematic radio and X-ray follow-up free of major selection effects (must include optically and gamma-ray dark events).***

- Prospects for detection in the next 10 years?
  - ***Large populations studies enabled only by next generation (XG) GW detectors.***

- What is needed?
  - ***XG GW detectors: NS-NS progenitors up to SF peak and localizations < 0.1 deg^2 for >10 events/yr (enabling radio and X-ray follow up independent of optical and gamma rays);***
  - ***Swift-like mission (short GRBs with arcmin localization) for on-axis events up to SF peak;***
  - ***Sensitive X-ray (Chandra-like) and radio (ngVLA) facilities;***
  - ***Theory: Linking progenitor physics to central engines and jet-launching mechanisms.***

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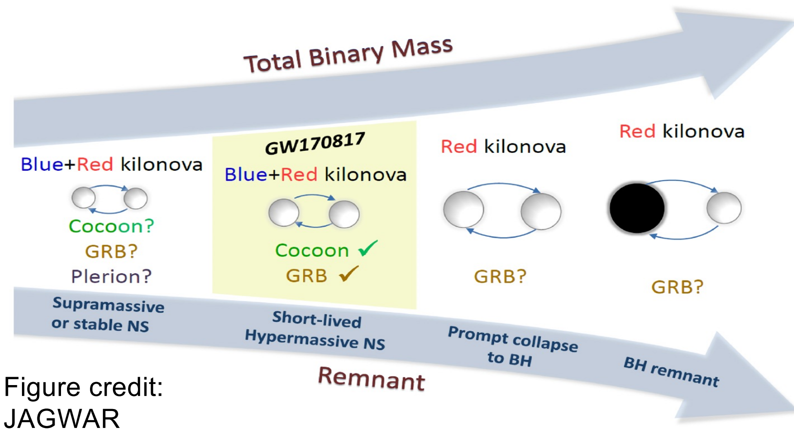

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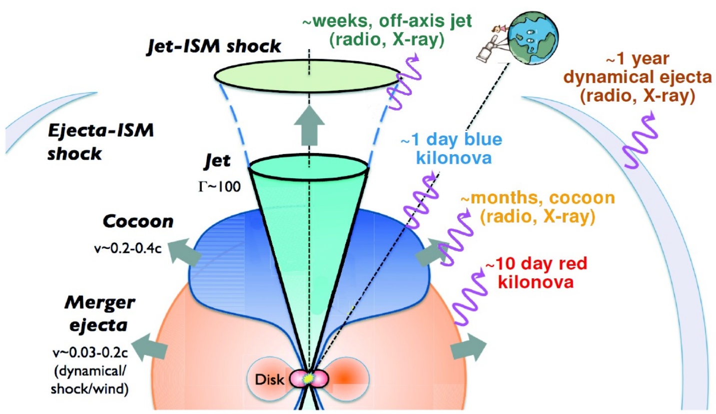
JAGWAR



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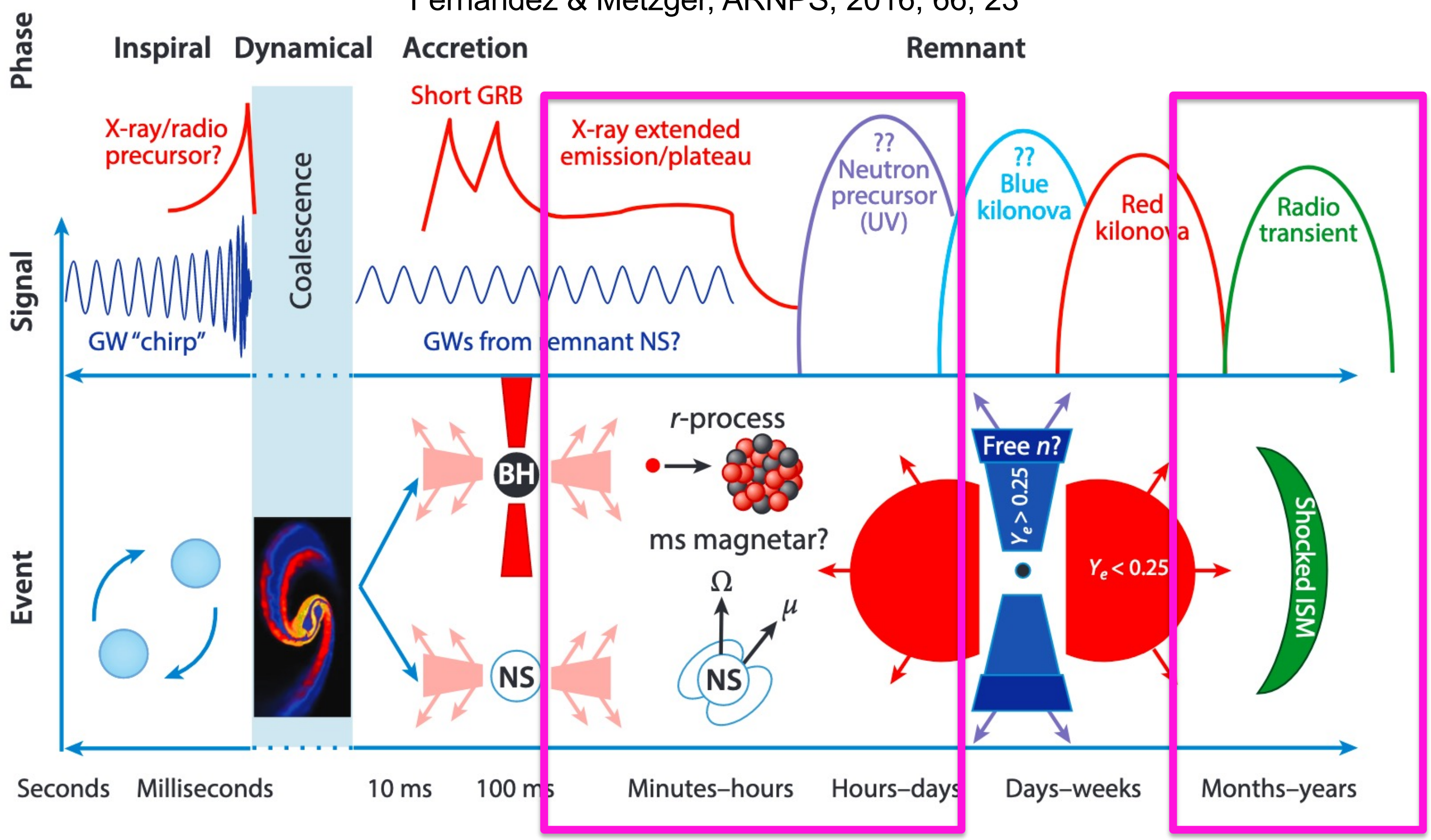
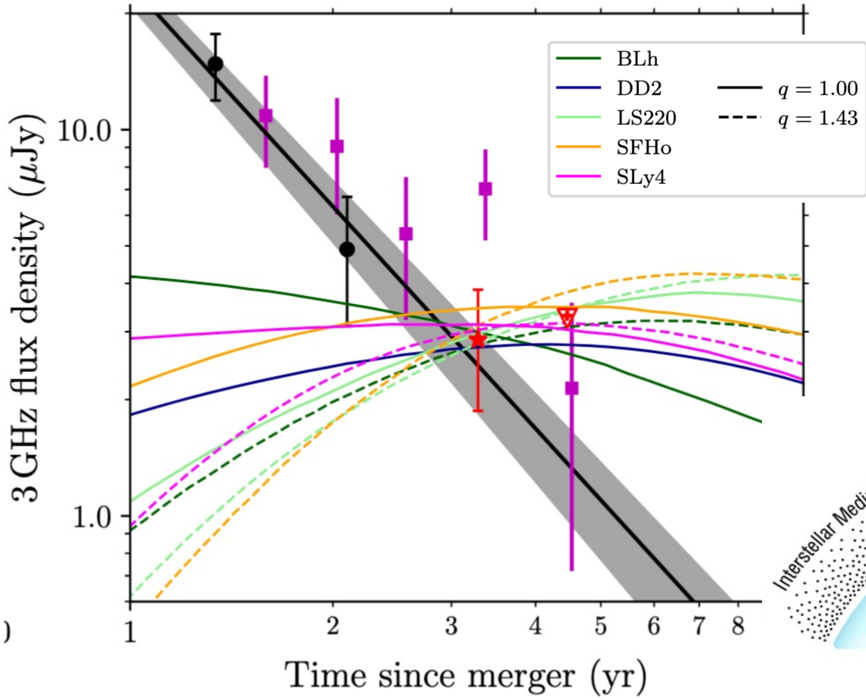
Yet-to-be-discovered counterparts

Fernandez & Metzger, ARNPS, 2016, 66, 23

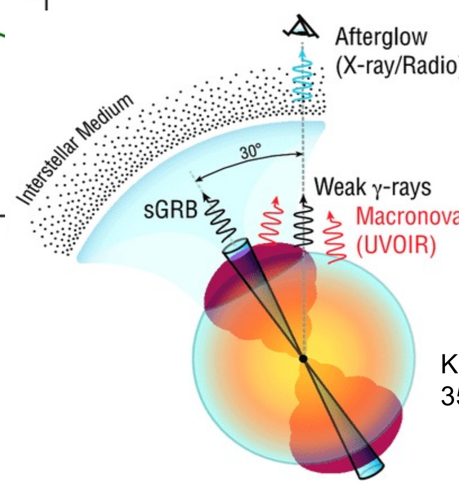


Nakar & Piran 2011, Nature, 478, 82

Kilonova late-time radio afterglow and EoS



Balasubramanian, Corsi, et al., ApJ submitted, arXiv:2205.14788



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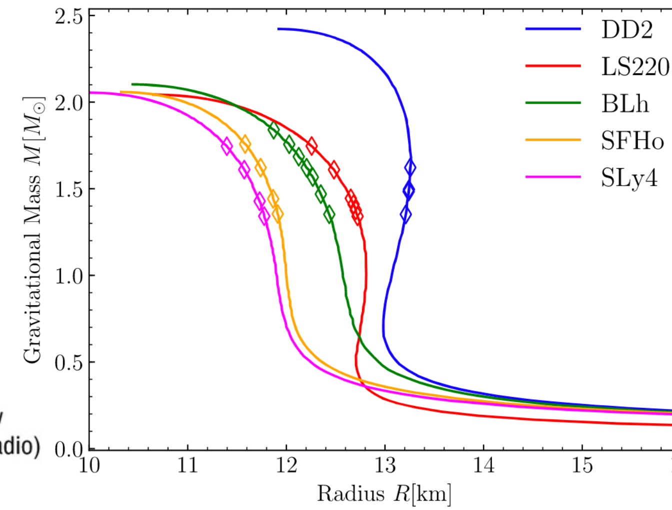
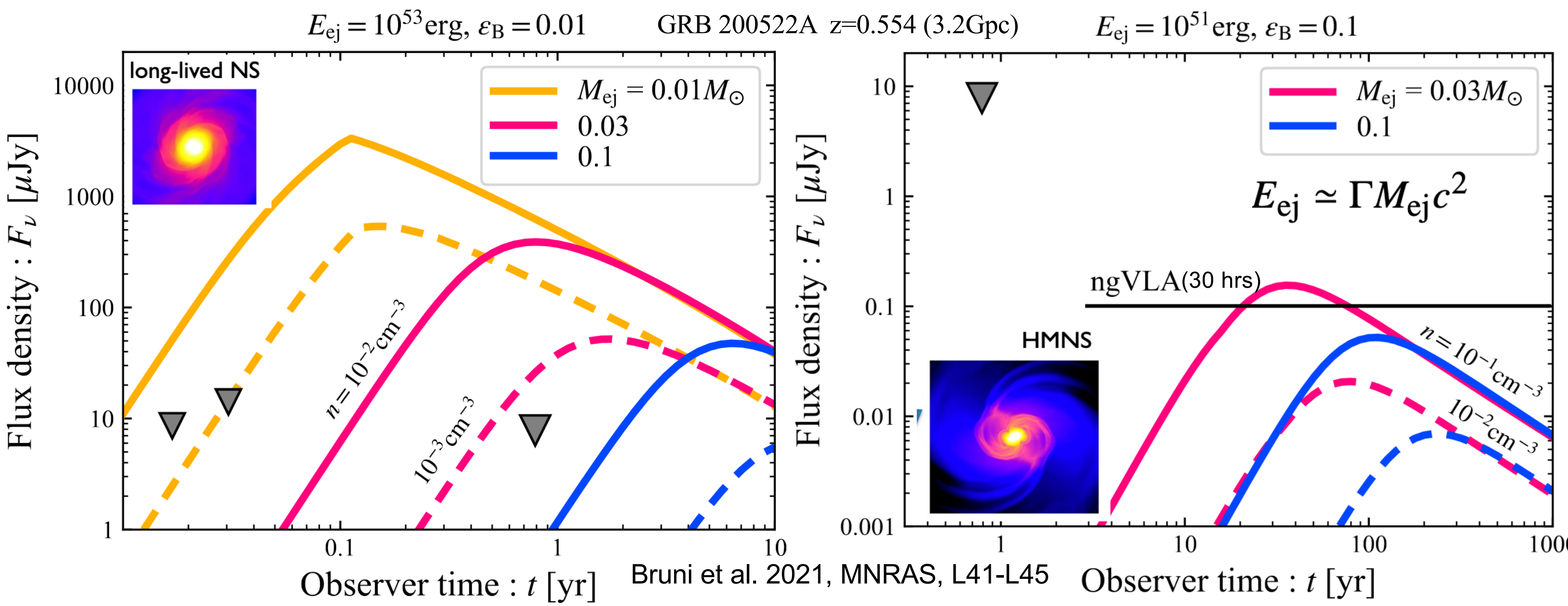


Nedora et al. 2021, ApJ, 906, 98

Late-time radio follow-up & nature of the merger remnant



Cosmological short GRBs at z<=0.5 with ~10uJy sensitivity @GHz frequencies set upper limits at the level of E_{ej}~10^{52} erg. **<~50% of GRBs make stable magnetars** (see also Schroeder et al. 2020, ApJ, 902, 82).

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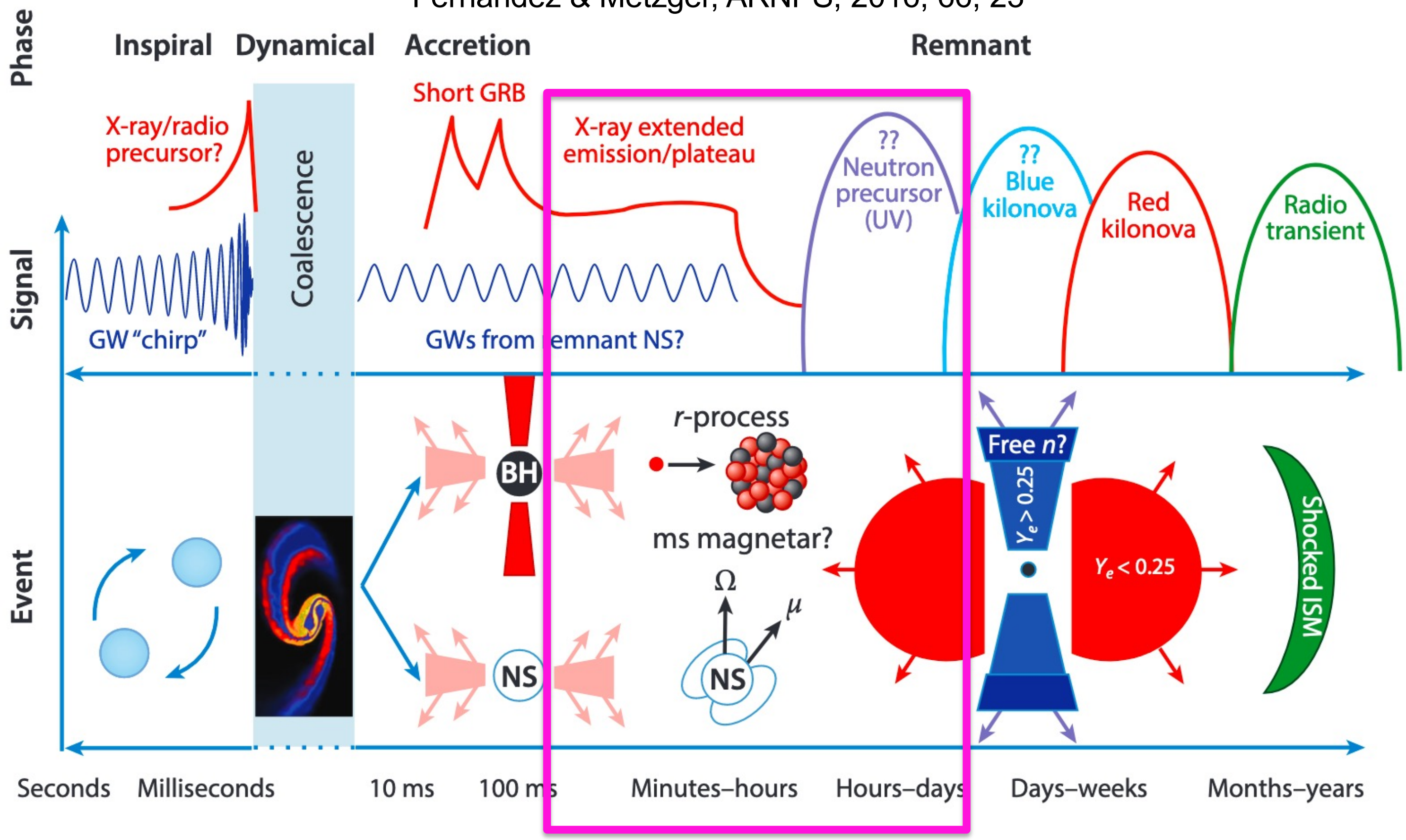
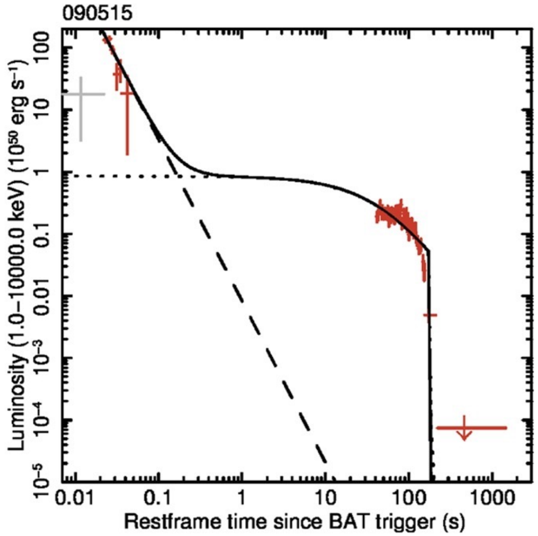
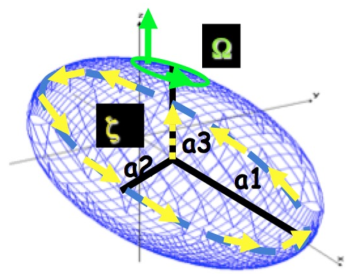


Merger remnant direct probe: post-merger GWs?



Rowlinson et al. 2013, MNRAS, 430, 1061



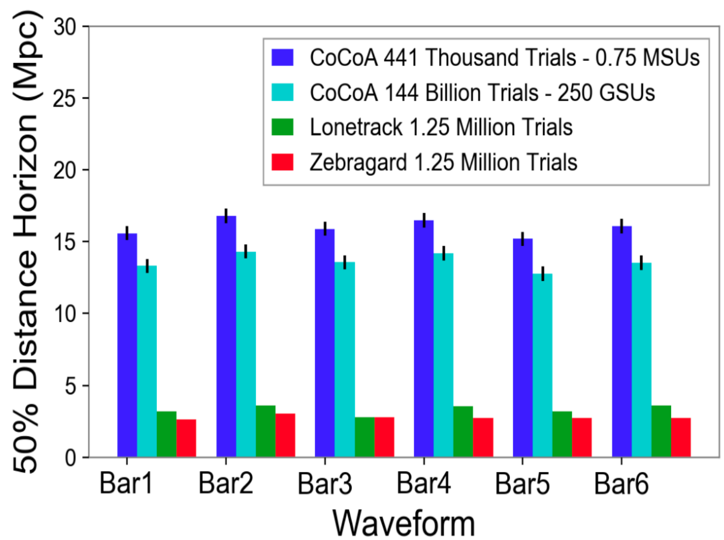
Riemann-S ellipsoid a1>a2>a3

$$\frac{dE}{dT} = -\frac{B_p^2 R^6 \Omega_{eff}^4}{6c^3} - \frac{32GI^2\epsilon^2\Omega^6}{5c^5} = L_{dip} + L_{GW}$$

Lai & Shapiro 1995, ApJ, 442, 259
Corsi & Meszaros 2009, ApJ, 702, 1171;
Coyne, Corsi, Owen, 2016, PRD, 93,104059;
Sowell, Corsi, Coyne 2019, PRD 100, 124041

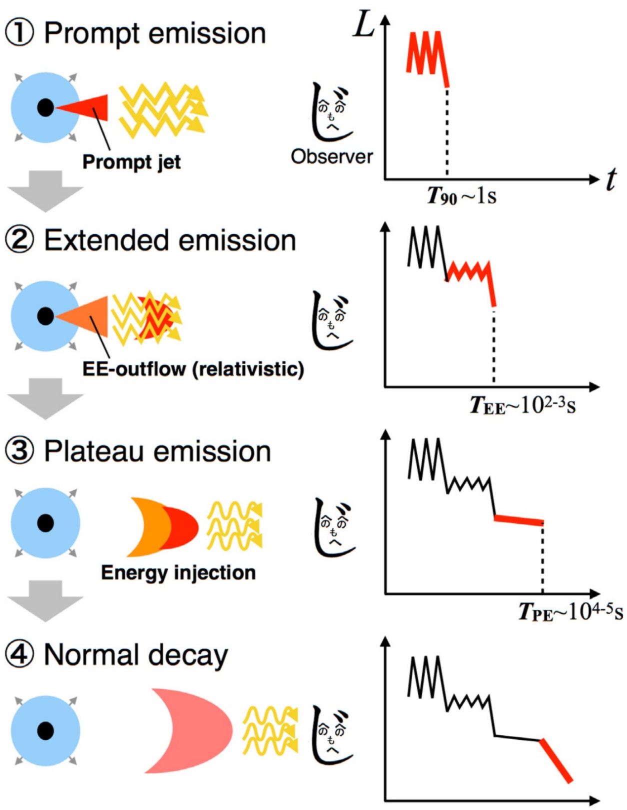
~15-35 Mpc in O2
~30-70 Mpc in O4 (Adv LIGO)
~55-130 Mpc in LIGO A+
~0.6-1 Gpc in CE

Bar-mode rates in CE: ~100-1000/yr × **fraction of BNS producing stable/quasi-stable NS remnants**

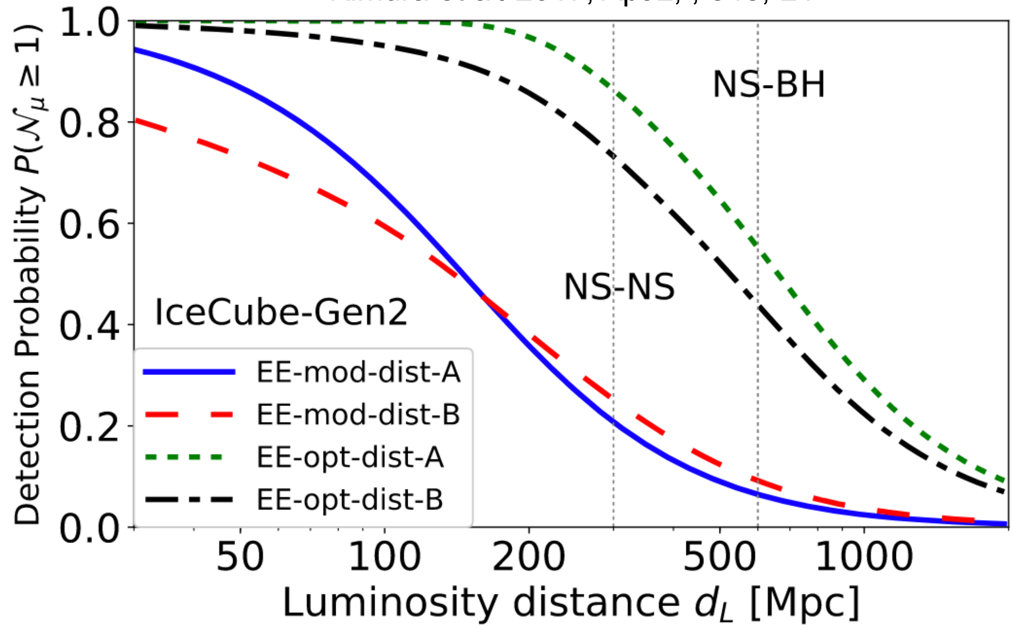


Next major discovery: GWs+EM+HEN?

Matsumoto et al. 2020, MNRAS, 493, 783



Kimura et al. 2017, ApJL, , 848, L4



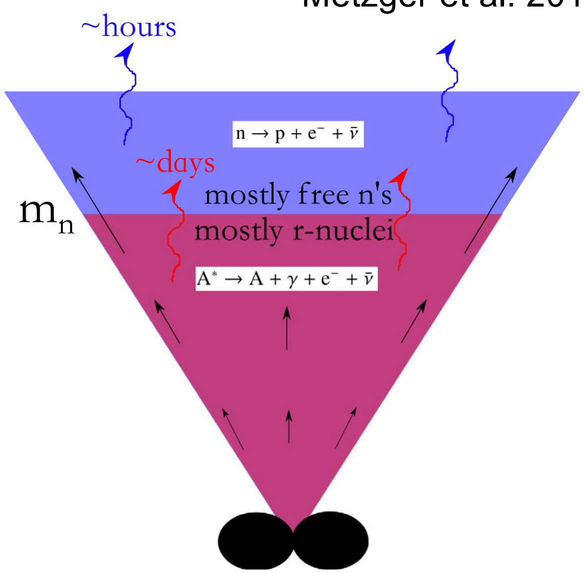
$$L_{\gamma,\rm iso} = 4\pi c\Gamma^2 r_{\rm diss}^2 U_{\gamma}$$

$$F(\Gamma) = \frac{dN_\Gamma}{d\ln\Gamma} = F_0 \exp\left(-\frac{(\ln(\Gamma/\Gamma_0))^2}{2(\ln(\sigma_\Gamma))^2}\right)$$

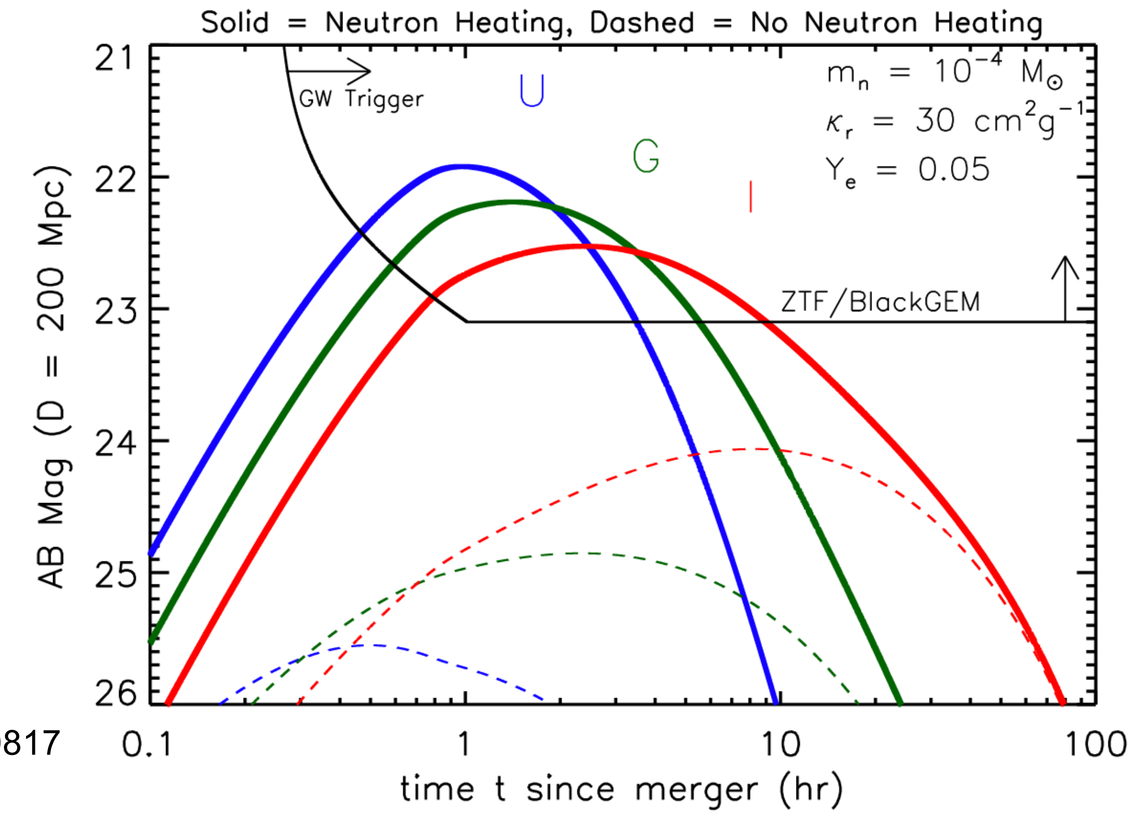
Mod → Γ_0 = 30
Opt → Γ_0 = 10
Dist-A → σ_Γ= 2
Dist-A → σ_Γ= 4

Early-time kilonova emission in the UV

Metzger et al. 2015, MNRAS, 446, 1115



200 Mpc



See also Arcavi 2018, ApJL, 855, L23 for impact of early UV observations in GW170817

3. What is the nature of the merger remnant? Early-time post-merger GW/EM/neutrino emission and **very-late-time** radio/X-ray follow up.

- Time-domain/multi-wavelength observations critical for answering these questions?
  - ***Observations in GWs, UV, X-rays, and neutrinos within ~1 hour since merger;***
  - ***Very-late-time (years after the merger) radio (and X-ray) observations.***

- Prospects for detection in the next 10 years?
  - ***GW+EM+neutrino during plateau/extended emission: high-risk high-reward;***
  - ***~ 25 % of SGRBs are accompanied by EE (Sakamoto et al. 2011);***
  - ***UV signatures promising;***
  - ***Late-time kilonova radio afterglow predicted and searched for in GW170817…***

- What is needed?
  - ***Enhanced sensitivity of XG detectors (for post-merger GWs);***
  - ***Ice-cube gen-2-like neutrino detectors;***
  - ***Prompt X-ray and UV observational capabilities (UVEX selected for MIDEX Phase A);***
  - ***Sensitive radio arrays (ngVLA).***

Fundamental science questions needing answers

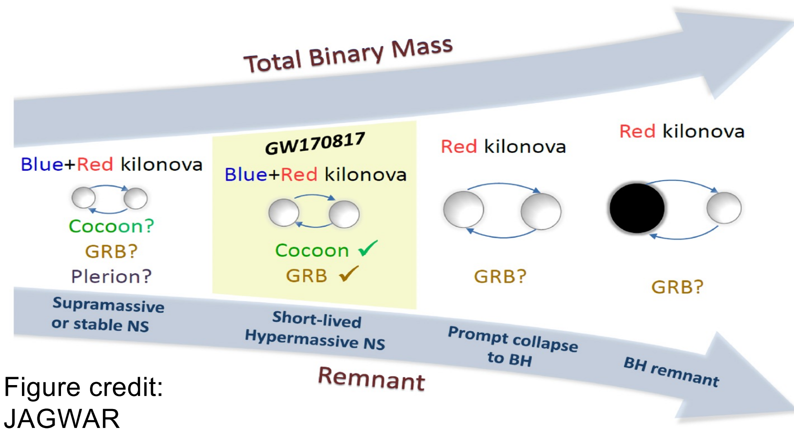
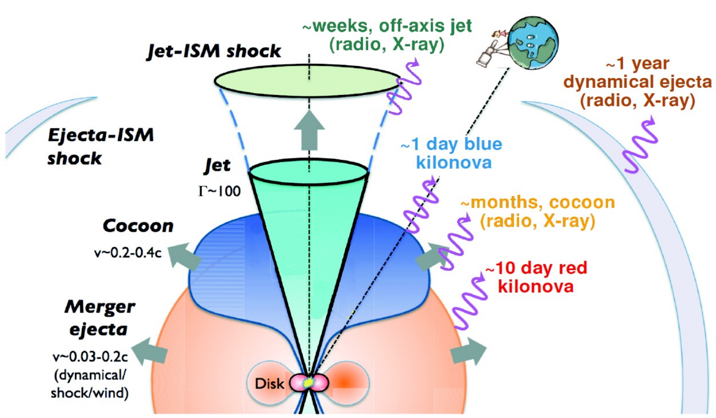


Figure credit:
JAGWAR



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Diverse and yet-to-be-discovered counterparts

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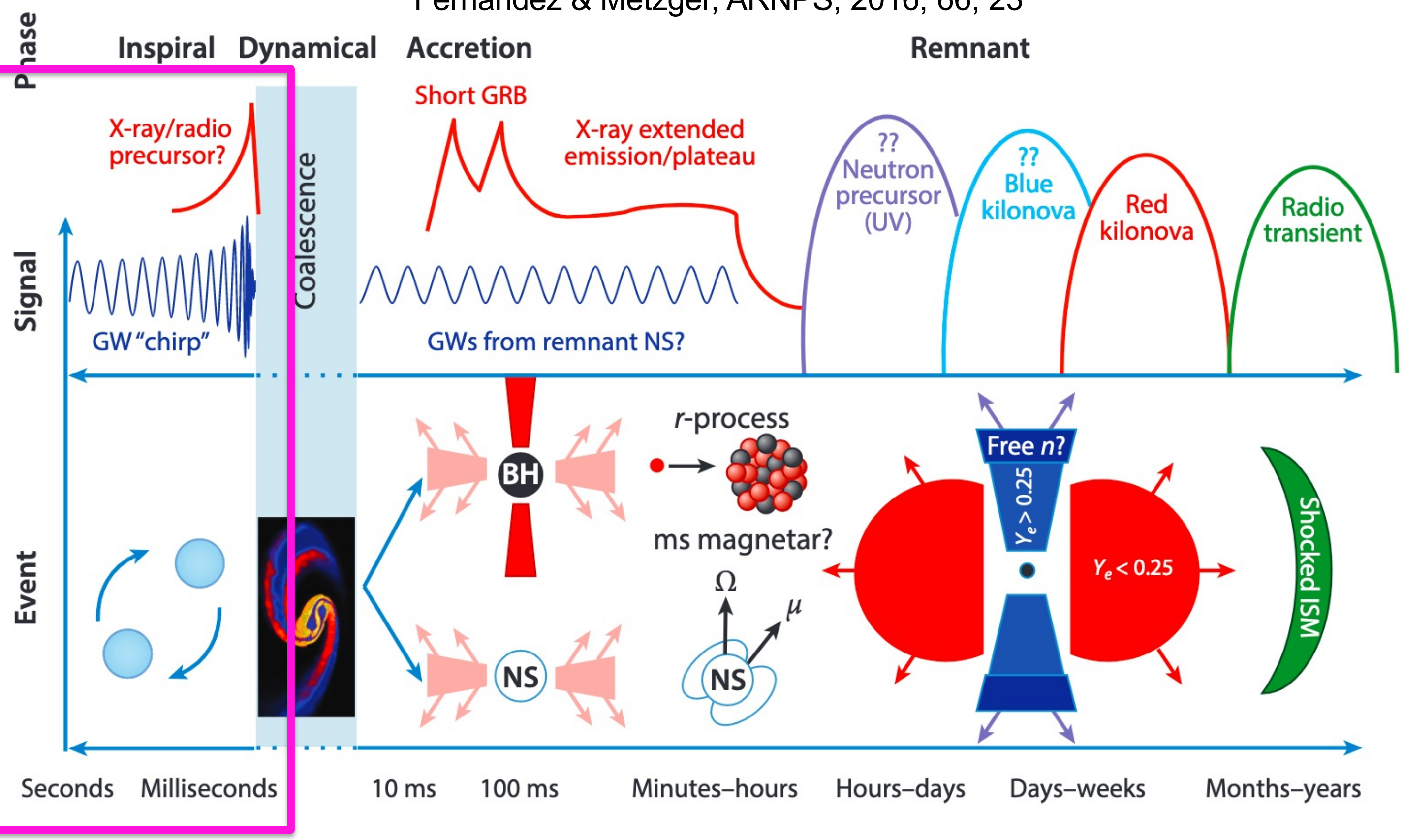
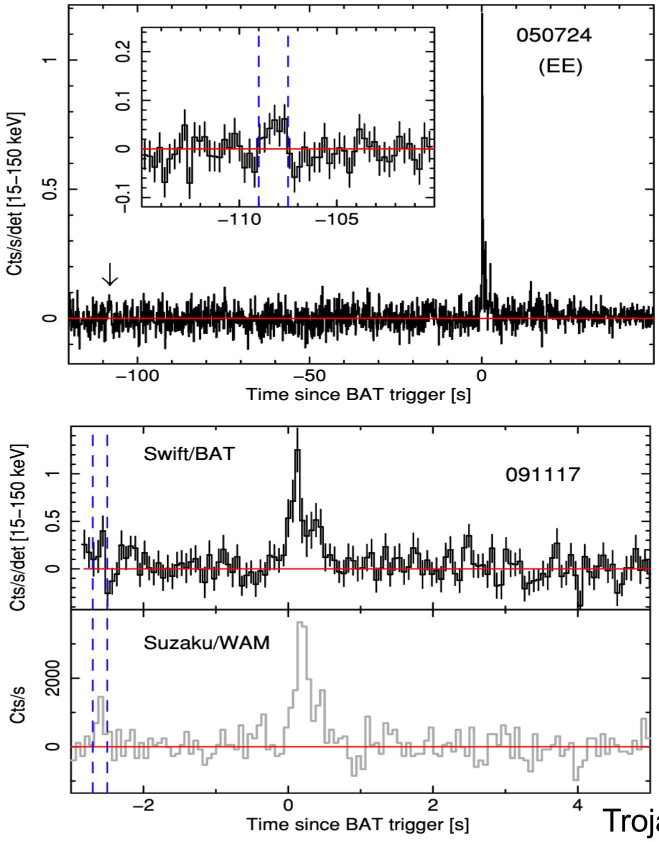


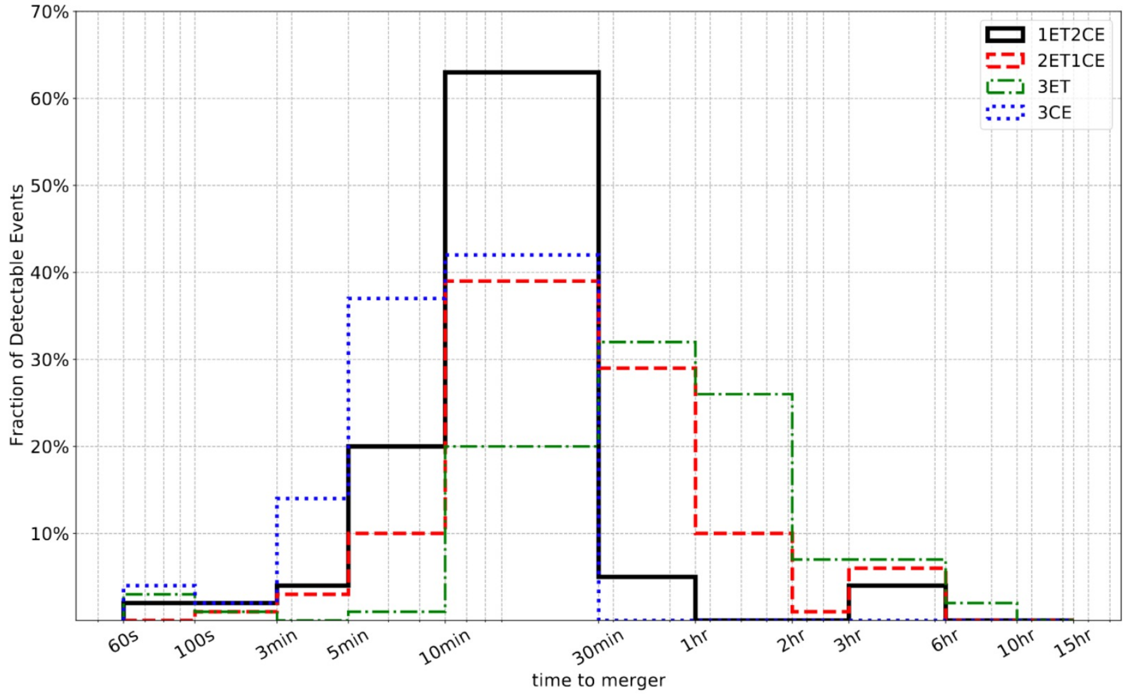
EM precursors

- Several models theorize prompt/precursor counterparts to NS-NS/BH-NS mergers that, unlike the KN or the emission from ejecta/jets interaction with the ISM, **are related to processes internal to the merging objects (and their magnetospheres).** Proposed scenarios include:
  - **Radio and X-ray signatures** (e.g., Hansen & Lyutikov, 2001, MNRAS, 322, 695; Lai 2012, ApJL, 757, L3; Piro 2012) related to interaction of a non-magnetized NS moving through another NS's magnetosphere;
  - **Explosive fireball models** (e.g., Metzger & Zivancev 2016, MNRAS, 461, 4435);
  - **Gamma-ray flares from resonant shattering of NS crusts** (e.g., Tsang et al. 2012, PRL, 108, 011102);
  - **Pulsar-like or shock-powered coherent radio precursors** (e.g., Wang et al. 2016, ApJL, 822, L7; Sridhar et al. 2021, MNRAS, 501, 3184).
  - **Recent review**: Wang & Liu, Galaxies 2021, 9, 104 (includes non-internal models such as cocoon shock breakout).

GRB precursors and GW early warning



Troja et al. 2010, ApJ, 723, 1711



(c) $10\mathrm{deg}^2$

Li et al. 2022, PRD 105, 043010

5. Physics of the progenitors via **EM precursors.**

- Time-domain/multi-wavelength observations critical for answering these questions?
  - ***Pre-merger multi-band (from high energy to radio) observations.***
- Prospects for detection in the next 10 years?
  - ***Uncertain. 8-10% of short GRBs show precursors.***
- What is needed?
  - ***Enhanced sensitivity of XG detectors for early warning with relatively good localizations.***
  - ***Gamma-ray/X-ray detectors with relatively large FOV;***
  - ***Low frequency radio arrays (coherent emission).***

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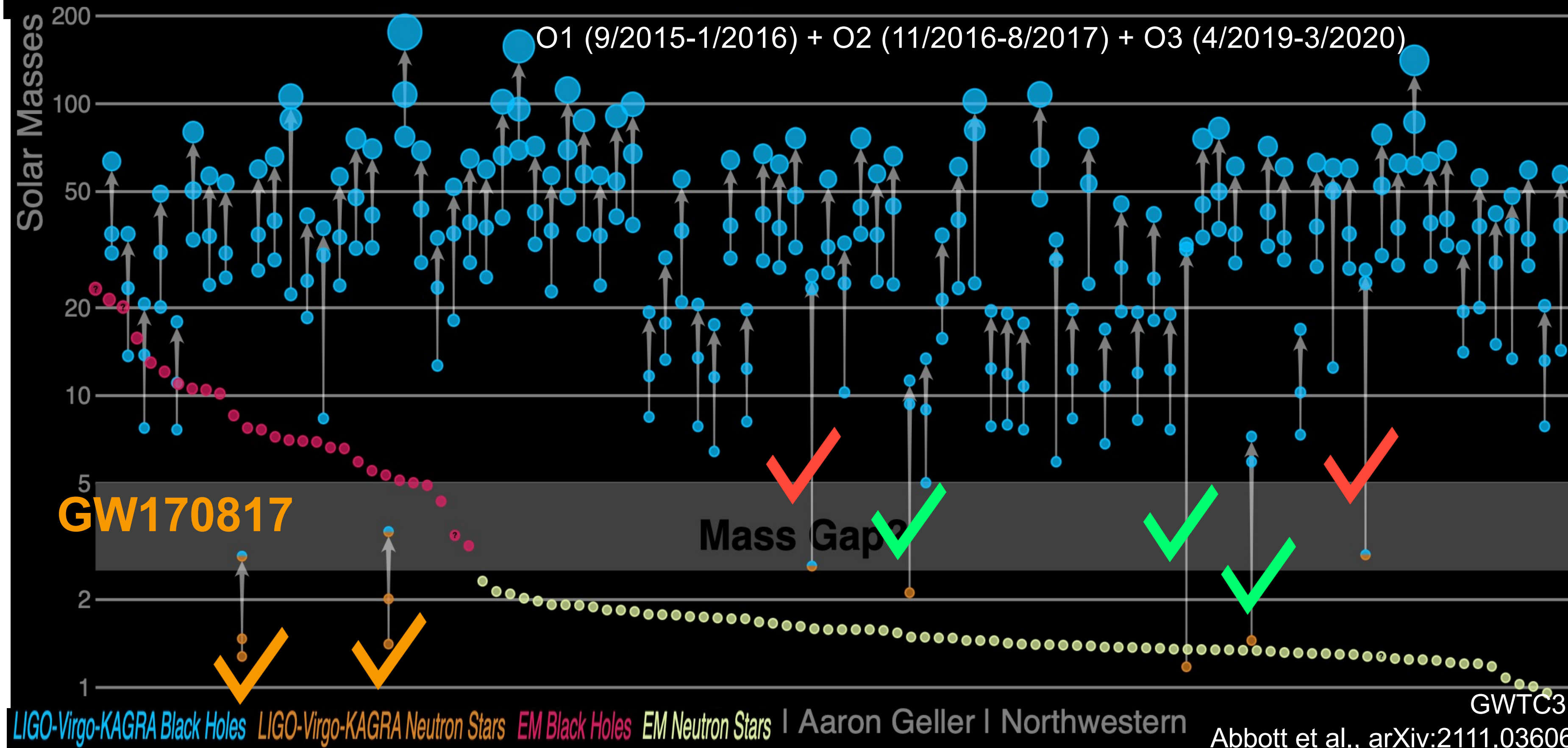
Masses in the stellar graveyard



GWTC3:
Abbott et al., arXiv:2111.03606